INCREASED OIL PRODUCTION AND RESERVES UTILIZING SECONDARY/TERTIARY RECOVERY TECHNIQUES ON SMALL RESERVOIRS IN THE PARADOX BASIN, UTAH

Contract No. DE-FC22-95BC14988

Utah Geological Survey (UGS), Salt Lake City, Utah 84114-6100

Submitted: June 1999

Award Date: February 9, 1995

Anticipated Completion Date: August 31, 2002

Government Award for Current Fiscal Year: $626,324

Principal Investigator: M. Lee Allison, UGS

Program Manager: Thomas C. Chidsey, Jr., UGS

Contracting Officer's Representative: Gary D. Walker, National Petroleum Technology Office, Tulsa, Oklahoma

Reporting Period: January 1 - March 31, 1999

Objectives

The primary objective of this project is to enhance domestic petroleum production by demonstration and technology transfer of an advanced oil recovery technology in the Paradox basin, southeastern Utah. If this project can demonstrate technical and economic feasibility, the technique can be applied to about 100 additional small fields in the Paradox basin alone, and result in increased recovery of 150 to 200 million barrels of oil. This project is designed to characterize five shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation and choose the best candidate for a pilot demonstration project for either a waterflood or carbon dioxide-(CO_2-) flood project. The field demonstration, monitoring of field performance, and associated validation activities will take place in the Paradox basin within the Navajo Nation. The results of this project will be transferred to industry and other researchers through a petroleum extension service, creation of digital databases for distribution, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, and publication in newsletters and various technical or trade journals.

Summary of Technical Progress

Two activities continued this quarter as part of the geological and reservoir characterization of productive carbonate buildups in the Paradox basin: (1) reservoir diagenetic analysis of fields (Fig. 1), and (2) technology transfer.

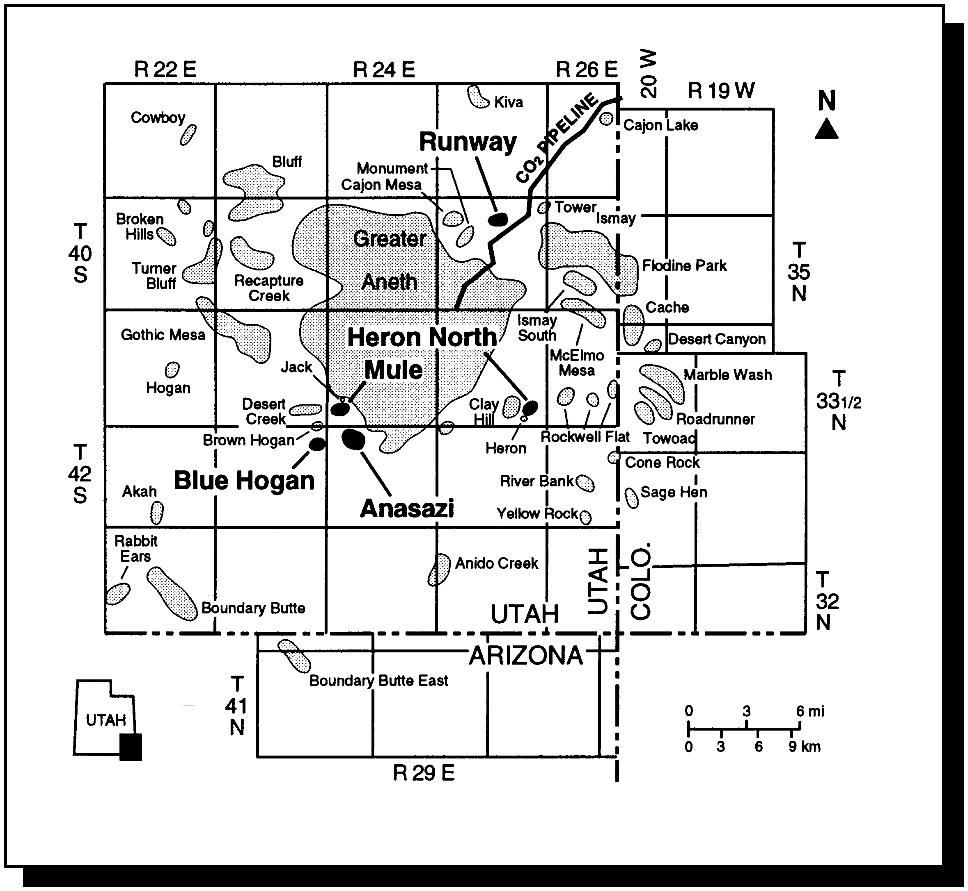

Fig. 1. Location of project fields (dark-shaded areas with names in bold type) in the southwestern Paradox basin on the Navajo Nation, San Juan Co., Utah.

Reservoir Diagenetic Analysis of Project Field Reservoirs

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of each field can be an indicator of reservoir flow capacity, storage capacity, and potential for water and/or CO_2 flooding. We analyzed the reservoir diagenetic fabrics and porosity types of these buildups to: (1) predict facies patterns, (2) determine the sequence of diagenetic events, and (3) provide data input for the reservoir modeling and simulation studies. In order to determine the diagenetic histories of the various Desert Creek reservoirs, 50 thin sections of representative samples were selected from the conventional cores of each field for petrographic description and to evaluate shallow-shelf/shelf-margin phylloid-algal, bryozoan, and calcarenite carbonate buildups. Carbonate fabrics were determined according to Dunham's[1] and Embry and Klovan's[2] classification schemes.

Diagenetic characterization focused on reservoir heterogeneity, quality, and compartmentalization within each of the five project fields. All depositional, diagenetic, and porosity information was placed into the context of the production history of each field in order to construct a detailed overview for each enhanced recovery candidate. Determination of the most effective pore systems for oil drainage versus storage is of special interest to reservoir engineers.

Diagenetic Environments

Most shallow-shelf/shelf-margin carbonate buildups or mounds were subaerially exposed when sea level fell during various times in the Pennsylvanian. This setting produced four major, generally early, diagenetic environment zones (Figs. 2 and 3): (1) a fresh-water (meteoric) vadose zone (above the water table, generally at or near sea level), (2) a meteoric phreatic zone (below the water table), (3) a marine phreatic zone, and (4) a mixing zone.[3] The "iceberg" principle (the Ghyben-Herzberg theory) can generally be applied to both carbonate mound and island buildups. This principle states that for every foot the water table rises above sea level there may be 20 ft (6.1 m) of fresh water below the water table, a 1:20 ratio.[4] Neomorphism, leaching/dissolution, and fresh-water cementation (dog-tooth, stubby, and small equant calcite) took place within the vadose and fresh-water phreatic zones.

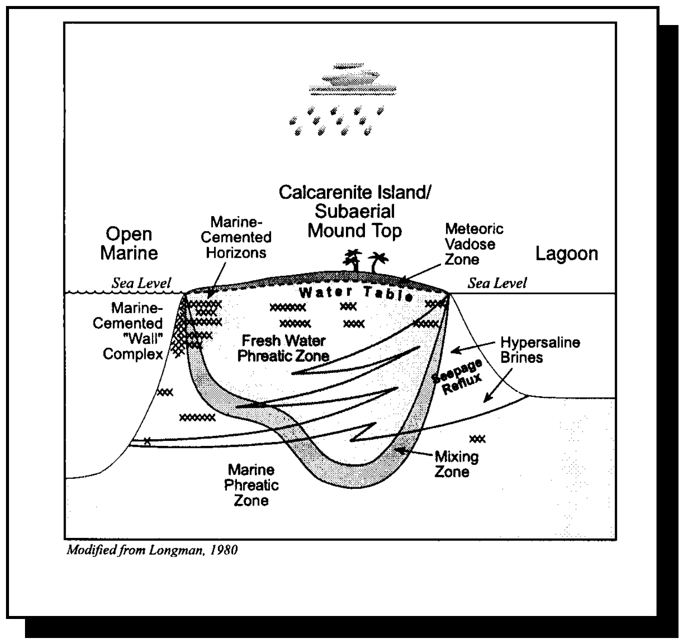

Figure 2. Diagrammatic cross section showing distribution of the early diagenetic environments of subaerially exposed shallow-shelf/shelf margin carbonate buildups or mounds found in the Desert Creek zone of the Paradox Formation, southern Paradox basin.

The meteoric and marine phreatic zones were separated by a mixing zone (fresh and sea water); the location of these zones changed with sea level fluctuation. Early dolomitization took place in the mixing zone. Most carbonate buildups (fields) have a mixing zone as well as a fresh-water overprint.

That portion of the carbonate buildup facing the open-marine environment was generally a steep-wall complex where early-marine cements (such as fibrous isopachous, botryoidal, and radiaxial cements) were deposited from invading sea water flowing through the system. The opposite side of the mound typically bordered a hypersaline lagoon filled with dense brine that seeped into the phreatic zone (seepage reflux) to form a wedge-shaped zone of low-temperature dolomite, both early replacement dolomite and dolomite cement.

Late (post-burial) diagenesis included syntaxial cementation, silicification, late calcite spar, saddle dolomite, stylolitization, bitumen plugging, and anhydrite replacement (Fig. 3). There is an observed progression from least to most important (syntaxial cementation to anhydrite replacement) in terms of the effects on reservoir quality in the case-study fields. Syntaxial cementation and silicification have relatively little effect whereas anhydrite replacement can greatly reduce reservoir quality. Some of these late diagenetic products create barriers and baffles to fluid flow, increasing reservoir heterogeneity. They are not observed on seismic records, are difficult to predict, and locally influence reservoir performance, storage capacity, and drainage. Finally, these post-burial diagenetic processes are not as significant in the case-study fields as earlier diagenetic modifications.

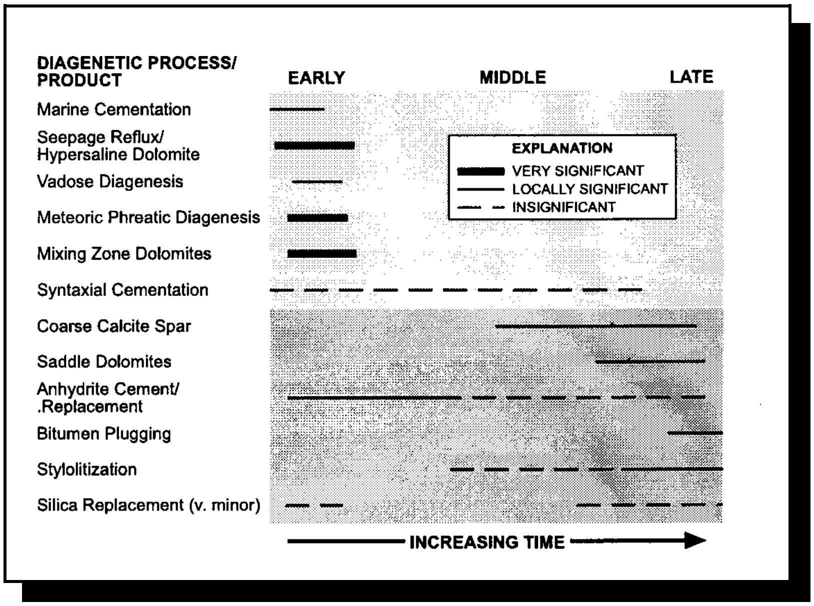

Fig. 3. Ideal diagenetic sequence through time, including processes and products.

Characteristics of Marine Cementation

Early marine cementation occurs in two settings: (1) the "wall" complex on the windward side (botryoidal fans and radiaxial blade cements) of the buildup, and (2) scattered horizons across interiors of buildups (fibrous isopachous and micritic cements). Slabbed core segments from the Blue Hogan No. 1-J-1 well, Blue Hogan field, show the typical pattern of marine cementation within the well-lithified "wall" complex at the higher energy margin of a small phylloid-algal mound (Fig. 4). Isopachous bands of cements and small Neptunian dikes are characteristic of the "wall." Figure 5 shows two generations of probable marine cements. The earlier generation was a brown micritic to microfibrous cement which was followed by a bladed, radiaxial generation of cement. Radiaxial cements filled most of the original pore space.

Cemented zones can have a major impact locally on reservoir flow and storage capacity. Pervasive marine cement within a "wall" complex may indicate a nearby buildup/mound.

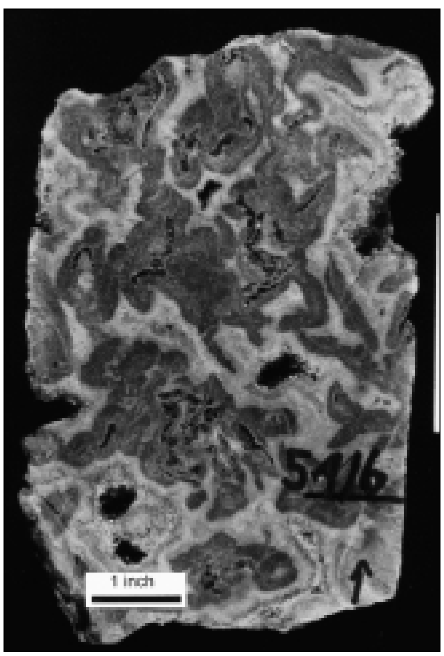

Fig. 4. Slabbed core segments from 5415.5 to 5416.1 ft (1650.6-1650.8 m) from the Blue Hogan No. 1-J-1 well showing the typical pattern of marine cementation within the well-lithified "wall" complex. Arrows indicate small Neptunian dikes.

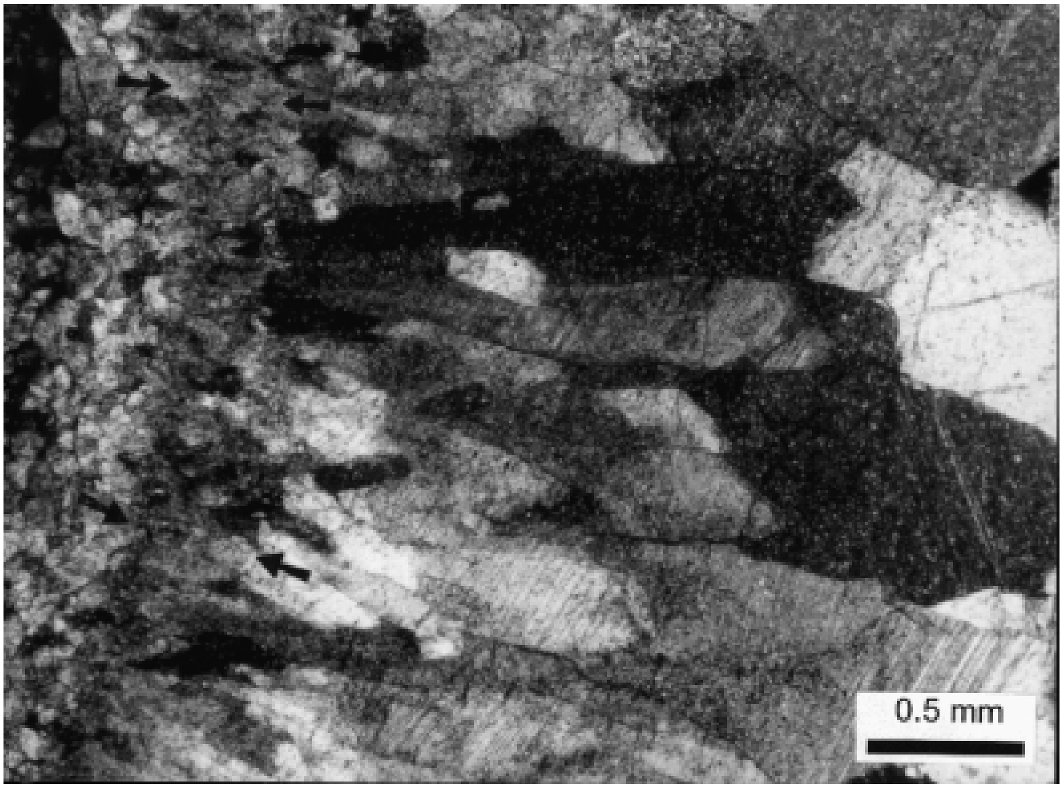

Fig. 5. Photomicrograph (crossed nicols) of two generations of probable marine cements. Blue Hogan No. 1-J-1 well, 5420.3 ft (1652 m), Blue Hogan field. The earlier generation was a micritic to microfibrous cement (between arrows) which was followed by a bladed, radiaxial generation.

Characteristics of Meteoric Diagenesis (in Limestone Facies)

In many of the project fields, that portion of the buildup affected by fresh water is the thickest of all diagenetic environmental zones and the processes which occurred there had the greatest potential for increasing reservoir quality. The depth/thickness of the meteoric vadose and fresh-water phreatic zones is dependent on the extent and duration of subaerial exposure as well as the amount of meteoric water influx. Dissolution creating molds, vugs, and channels, is the dominant porosity-enhancing process of meteoric diagenesis (Fig. 6). Much of the original fabric remains or can be determined. Early dissolution of lime muds creates microporosity. Indicative cements include stubby to equant calcite and "dogtooth" calcite spars which sporadically line pores (Fig. 7). Vadose zones generally have less cement than the fresh-water phreatic zones.

Locally, meteoric diagenesis enhances reservoir performance. Extensively leached intervals may have both excellent storage and flow capacity, and should be considered candidates for CO_2-flooding projects. Microporosity from lime mud and dissolution increases storage capacity but limits fluid recovery.

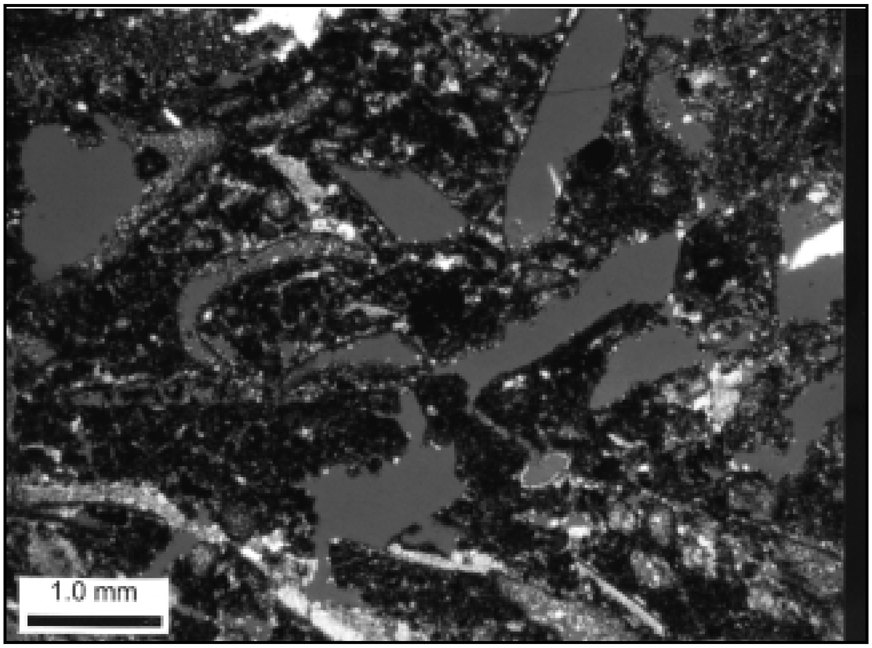

Fig. 6. Photomicrograph (plane light) of interconnected solution channel and moldic porosity with very little visible meteoric cements (porosity = 13.2%, permeablility = 20.4 millidarcies [md] by core-plug analysis). Mule No. 31-M well, 5729.8 ft (1746.4 m), Mule field.

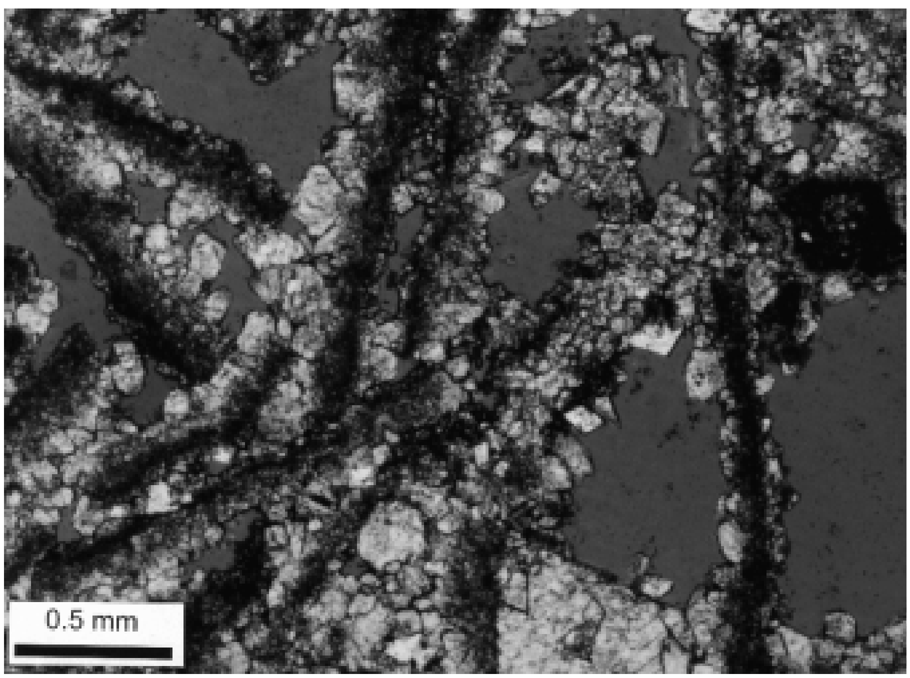

Fig. 7. Photomicrograph (plane light) of early solution porosity within a phylloid-algal facies partially occluded by stubby to equant to "dogtooth" spar cements of probably meteoric phreatic origin (porosity = 12.5%, permeability = 53.8 md by core-plug analysis). These types of cements have decreased the permeability of these solution-enhanced pore systems. Runway No. 10-C-5A well, 6127.4 ft (1867.5 m), Runway field.

Characteristics of Dolomitization

Dolomization can be divided into two types, mixing zone and seepage reflux, each with different characteristics (Fig. 8). Mixing zone dolomitization is usually incomplete dolomitization (as shown by the presence of fine-grained crystals). Some of the original fabric, micritization, and/or evidence of fresh-water dissolution often still remains. There are variable percentages of micro-intercrystalline and intercrystalline porosity. Mixing zone dolomitization units are generally thinner than intervals affected by other diagenetic processes. The depth of the mixing zone is dependent on the thickness of the fresh-water phreatic zone, the volume of fresh water available, and/or the amount of subaerial exposure. Locally, mixing zone dolomitization may reduce or enhance reservoir performance. Affected intervals may have a modest to good storage capacity; flow capacity can be highly variable.

Seepage reflux dolomization is usually complete dolomitization. Little original fabric/matrix remains. Crystals are fine to medium grained, often sucrosic; intercrystalline porosity dominates (Fig. 9). Seepage reflux dolomization occurs in mounds associated with lagoons where hypersaline brines are concentrated. It overprints the fresh-water phreatic, marine phreatic, and mixing zones across the entire extent of the mound buildup. Thick seepage reflux dolomites are often proximal to evaporite-plugged lagoonal sediments. Locally, seepage reflux

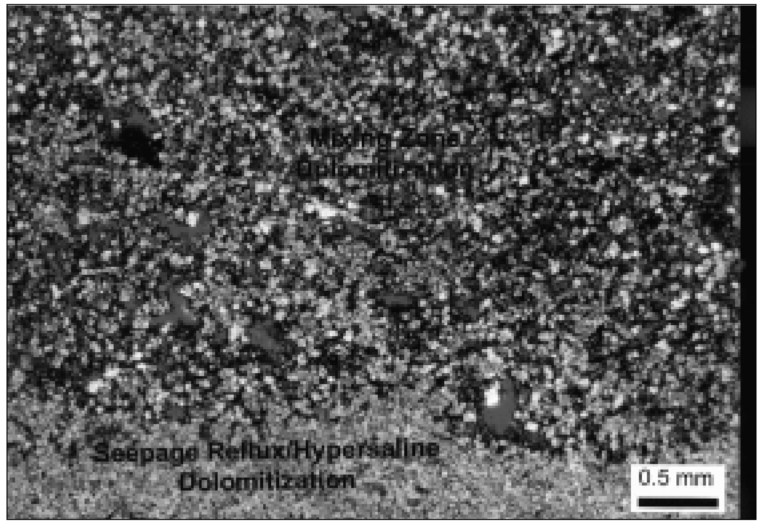

Fig. 8. Photomicrograph (plane light) of a dolomitized wackestone/packstone showing the contrast between probable seepage reflux/hypersaline dolomitization toward the base and more porous mixing zone dolomitization above (porosity = 20.3%, permeability = 39.8 md by core-plug analysis). Note the ghosts of probable ostracods and crinoids. Runway No. 10-C-5A well, 6120.2 ft (1865.3 m), Runway field.

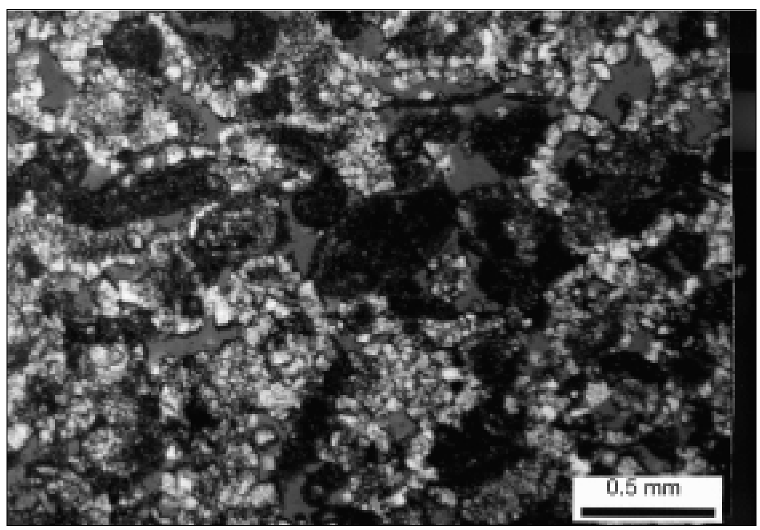

Fig. 9. Photomicrograph (plane light) of dolomitized, well sorted, pelloidal/oolitic/bioclastic grainstone; porosity = 13.4%, permeability = 33.9 md by core-plug analysis. Note the very fine crystalline dolomite formed by seepage reflux processes followed by partial dissolution and other meteoric overprints. The combination of both processes have led to good storage potential and excellent flow capacity. North Heron No. 35-C well, 5569.2 ft (1697.4 m), Heron North field.

dolomitization can enhance both reservoir flow and storage capacity. Those reservoirs with excellent storage capacity may be considered candidates for CO_2-flooding projects.

Technology Transfer

David E. Eby presented a talk entitled *Upper Devonian Carbonate Buildups Impersonating Paradox Basin Phylloid Algal Mounds* at the monthly meeting of the Utah Geological Association on January 11, 1999. The discussion compared the geologic characterization of carbonate mound buildups within the Paradox basin to potentially hydrocarbon productive Devonian buildups in western Canada and eastern Europe.

An abstract presenting the geological characterization of the carbonate buildup/reservoir in Mule field (Fig. 1) was submitted and accepted for presentation at the American Association of Petroleum Geologists (AAPG) Rocky Mountain Section meeting in Bozeman, Mont., August 10, 1999. A paper was published by the AAPG describing the facies and reservoir characteristics of the project fields, and the Anasazi field modeling and simulation results.[5]

The project home page on the UGS Internet web site (http://www.ugs.state.ut.us/paradox.htm) was updated with the latest quarterly technical report and project publications list.

References

1. R. J. Dunham, Classification of Carbonate Rocks According to Depositional Texture, in Ham, W. E., ed., Classification of Carbonate Rocks: *Amer. Assoc. of Petrol. Geol. Mem.* 1: 108-121 (1962).

2. A. R. Embry, and J. E. Klovan, A Late Devonian Reef Tract on Northeastern Banks Island, Northwest Territories: *Canad. Petrol. Geol. Bull.* 19: 730-781 (1971).

3. M. W. Longman, Carbonate Diagenetic Textures from Nearshore Diagenetic Environments: *Amer. Assoc. of Petrol. Geol. Bull.* 64 (4): 461-487 (1980).

4. G. M. Friedman, and J. E. Sanders, *Principles of Sedimentology*: John Wiley and Sons, New York, N.Y. (1978).

5. S. L. Montgomery, T. C. Chidsey, Jr., D. E. Eby, D. M. Lorenz, and W. E. Culham, 1999, Pennsylvanian Reserves in Heterogeneous, Shallow-Shelf Reservoirs: *Amer. Assoc. of Petrol. Geol. Bull.* 83 (2): 193-210 (1999).

FIGURE CAPTIONS

Fig. 1. Location of project fields (dark-shaded areas with names in bold type) in the southwestern Paradox basin on the Navajo Nation, San Juan Co., Utah.

Fig. 2. Diagrammatic cross section showing distribution of the early diagenetic environments of subaerially exposed shallow-shelf/shelf margin carbonate buildups or mounds found in the Desert Creek zone of the Paradox Formation, southern Paradox basin (modified from Longman).[3]

Fig. 3. Ideal diagenetic sequence through time, including processes and products.

Fig. 4. Slabbed core segments from 5415.5 to 5416.1 ft (1650.6-1650.8 m) from the Blue Hogan No. 1-J-1 well showing the typical pattern of marine cementation within the well-lithified "wall" complex. Arrows indicate small Neptunian dikes.

Fig. 5. Photomicrograph (crossed nicols) of two generations of probable marine cements. Blue Hogan No. 1-J-1 well, 5420.3 ft (1652 m), Blue Hogan field. The earlier generation was a micritic to microfibrous cement (between arrows) which was followed by a bladed, radiaxial generation.

Fig. 6. Photomicrograph (plane light) of interconnected solution channel and moldic porosity with very little visible meteoric cements (porosity = 13.2%, permeablility = 20.4 millidarcies [md] by core-plug analysis). Mule No. 31-M well, 5729.8 ft (1746.4 m), Mule field.

Fig. 7. Photomicrograph (plane light) of early solution porosity within a phylloid-algal facies partially occluded by stubby to equant to "dogtooth" spar cements of probably meteoric phreatic origin (porosity = 12.5%, permeability = 53.8 md by core-plug analysis). These types of cements have decreased the permeability of these solution-enhanced pore systems. Runway No. 10-C-5A well, 6127.4 ft (1867.5 m), Runway field.

Fig. 8. Photomicrograph (plane light) of a dolomitized wackestone/packstone showing the contrast between probable seepage reflux/hypersaline dolomitization toward the base and more porous mixing-zone dolomitization above (porosity = 20.3%, permeability = 39.8 md by core-plug analysis). Note the ghosts of probable ostracods and crinoids. Runway No. 10-C-5A well, 6120.2 ft (1865.3 m), Runway field.

Fig. 9. Photomicrograph (plane light) of dolomitized, well sorted, pelloidal/oolitic/bioclastic grainstone; porosity = 13.4%, permeability = 33.9 md by core-plug analysis. Note the very fine crystalline dolomite formed by seepage reflux processes followed by partial dissolution and other meteoric overprints. The combination of both processes have led to good storage potential and excellent flow capacity. North Heron No. 35-C well, 5569.2 ft (1697.4 m), Heron North field.